

# Transient Characterization of a Propylene Loop Heat Pipe During Startup and Shut-down

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## ABSTRACT

A technology demonstration Loop Heat Pipe (LHP) has been tested extensively in support of the implementation of this two-phase thermal control technology on NASA's Earth Observing System Tropospheric Emission Spectrometer (TES) instrument. This cryogenic instrument is being developed at the Jet Propulsion Laboratory for NASA. This paper reports on the transient characterization testing results for a propylene LHP. Steady state performance and model correlation results can be found elsewhere [1].

In applications, when a component of large mass on an instrument or spacecraft is attached to a LHP evaporator, there is a concern that the LHP will not start when power is applied to the component until a significant temperature overshoot from the equilibrium temperature is developed. In some space applications, this may be a problem because the maximum allowable flight temperatures (AFTs) may be exceeded. Similarly, when power is removed from the component, there is a concern that the LHP will continue to operate, for some extended period of time, due to the sensible heat available from the large mass. Its important to understand the LHP behavior in such a situation in order to make reliable component temperature predictions for non-operating scenarios and to prevent component temperatures from dropping below the minimum non-operating AFT limits.

A test program was developed to characterize the start-up and shut-down transient behavior of a propylene LHP with a large mass attached to the evaporator. The LHP was tested over the expected operational temperature and power range during ground test operations and in flight for the TES instrument. In addition, a start-up heater was implemented on the LHP evaporator and tested under similar conditions. Transient results show the magnitude of the overshoot with and without the start-up heater. Recommendations are made for future applications and additional research on this topic.

## INTRODUCTION

Loop heat pipes have recently received increased attention within the aerospace thermal control community. A number of NASA and commercial programs have baselined both ammonia and propylene LHPs for thermal control.

LHPs are passive heat transport devices that use capillary forces to circulate a two-phase working fluid. They consist of a heat-accepting evaporator, heat-rejecting condenser, fluid reservoir and tubing to connect the components. The fundamental theory of LHP operation and detailed descriptions of applications can be found in various papers [2-14]. They were developed in the former Soviet Union in the early 1980's and have flown successfully in a number of space missions. These include the ALYONA flight experiment launched in 1989, the OBZOR optical instrument launched in 1994, both used propylene LHPs and to date both are still operating in space [2,3].

LHPs were selected for use on the TES instrument to solve two key thermal control problems: (1) while in survival mode the instrument equipment must be thermally decoupled from the nadir heat-rejecting radiators to conserve survival heater power and remain within the allocated budget, and (2) enable the packaging of equipment within the instrument envelope and meet the cable length and routing requirements as well as the structural design constraints. Ground test operations dictates that the thermal control system must operate in both horizontal and vertical orientations. Horizontal orientation refers to a condition with the condenser normal to the gravity vector and the evaporator below. Vertical position refers to the condenser parallel to the gravity vector and the evaporator at an elevation between the extreme rungs of the condenser. The implementation of LHPs provided the required design space to meet all the thermal, electrical, structural, and mechanical configuration requirements. A detailed description of the TES instrument thermal control system is available in Ref. 15.

In survival mode, the nadir radiators are exposed to a fairly cold space environment and experience orbital temperature variations between  $-96$  to  $-71^{\circ}\text{C}$  with an orbit period of 98 minutes. Ammonia freezes at  $-78^{\circ}\text{C}$ , and if used as the working fluid, would pose a serious risk for rupturing the condenser lines attached to the radiators. Propylene with a freezing point of  $-180^{\circ}\text{C}$  and with the most flight experience, and readily available, was selected instead. The heat transport capacity of propylene is lower when compared to ammonia. The conductance of a propylene LHP is 20-40% that of an ammonia LHP. For the TES application, the performance penalty paid for using propylene is acceptable.

### JPL'S LOOP HEAT PIPE TEST BED

A characterization testing program was initiated at JPL to support the implementation of this thermal control technology on the TES instrument. A fully automated test bed was developed to enable testing of LHPs in an ambient environment at any orientation and with capability to vary the condenser sink temperature, initial evaporator temperature and power to evaporator. In addition, heater power can be applied to compensation chamber or closed-loop temperature control can be used to control its temperature. The test bed is shown in Figs. 1-4. The test LHP is supported on a table, which can be rotated to any orientation, with the LHP fully instrumented. The LHP condenser is attached to a 1/8 inch aluminum radiator plate as shown in Fig. 1. A fluid cooling loop is then attached to the opposite side of this radiator plate to provide cooling. The evaporator saddle and condenser radiator plate are supported from the adjustable table using low conductivity G10 rods. An aluminum heater block, mounted to the evaporator saddle, with two calrod heaters is used for providing heat to the evaporator. Similarly, an aluminum cooling block with a fluid heat exchanger is attached to the opposite side of the evaporator saddle to actively control its temperature. The entire LHP is fully insulated with fiberglass and foam insulation material to minimize parasitic heat leaks.

An electronics rack with power supplies, temperature controller, thermocouple readout unit and a chiller, for fluid loop temperature control, was used for controlling and monitoring the test. A LabView™ program was written to automate the tests, provide real-time data monitoring and trending capability and save heater power and thermocouple data in a file.

### LHP TECHNOLOGY DEMONSTRATION UNIT

A copy of an existing LHP design was procured from Dynatherm Corporation Inc. to evaluate this technology. The design is based on a LHP manufactured for NASA GSFC's Geoscience Laser Altimeter System (GLAS). The evaporator consists of an all aluminum saddle/body

encasing a sintered nickel wick structure. The compensation chamber is made from stainless steel with flat end caps as shown in Figs. 5 and 6.

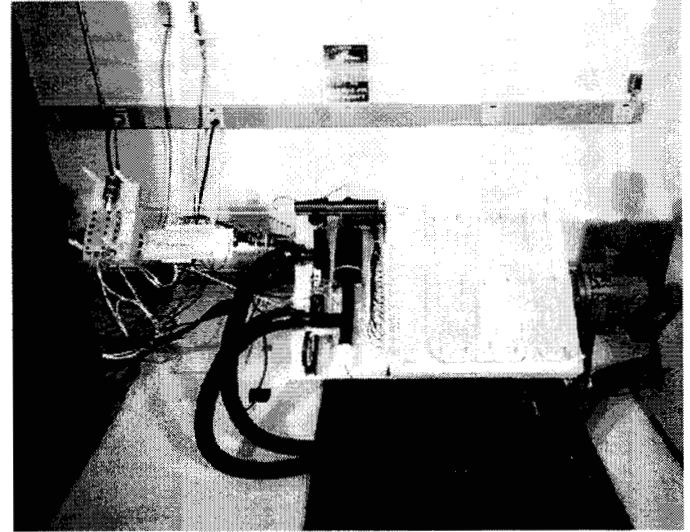


Figure 1. LHP test bed setup: support table

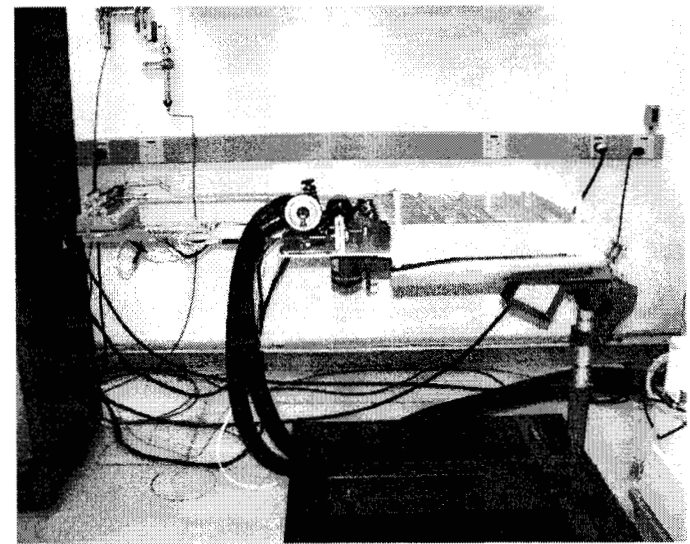


Figure 2. LHP test bed setup: horizontal table position

The transport lines are made from stainless steel tubing and the condenser is made from a single piece of flanged aluminum extrusion shaped into a serpentine configuration. The condenser is mounted on a 1/8 inch aluminum plate with another identical serpentine shape flanged extrusion bent into a mirrored image on the opposite side of the plate for providing a heat sink by using a cooling fluid loop. Fig. 7 shows the condenser mounted to the aluminum plate. The geometric parameters of the LHP are shown in Table 1. A schematic of the LHP with the thermocouple locations is illustrated in Fig. 8.

A large mass to simulate the TES equipment was attached to the evaporator to study startup and shutdown transients. The large mass consisted of a stack of copper blocks of the same width as the evaporator saddle. All tests were carried out with 21 kg of copper attached to the evaporator. Figs. 9 and 10 show the evaporator with the six copper blocks attached. The aluminum heater block is mounted to the top of the copper block stack.

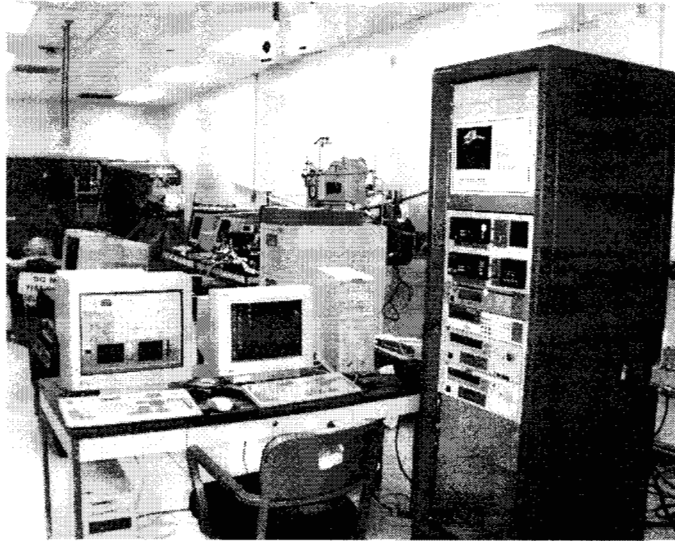


Figure 3. LHP test bed setup: electronics rack and data acquisition system

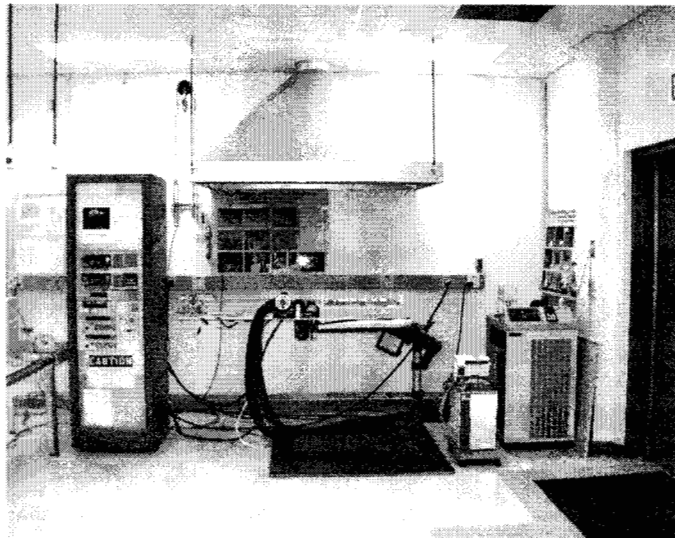


Figure 4. LHP test bed laboratory setup

The heat capacity of all six copper blocks including the aluminum heater and cooling blocks is 9,080 J/C. This is equivalent to 10.2 kg of aluminum. The equivalent aluminum mass of the evaporator, wick, compensation chamber and liquid core is approximately 0.81 kg. Prior

to startup, after power is applied to the large mass, the heater power is used to raise the temperature of the large mass/ evaporator assembly. Assuming parasitic heat leaks are negligible, the power delivered to the evaporator saddle/body can be obtained from a simple energy balance as follows:

$$Q_{LHP\ Evap} = (m/(M+m))Q_{mass}$$

where,  $m$  is the evaporator and compensation chamber assembly mass,  $M$  is the mass of the large mass,  $Q_{mass}$  is the heater power applied to the large mass.

Table 1. Key geometric parameter of test unit

Component		Description
Evaporator	Material	6061 AL
	I.D.	2.421 cm
	Length	15.24 cm
Primary wick	Material	Sintered nickel
	Pore size	1.2 $\mu$ m
	Porosity	0.60
	Permeability	$4 \times 10^{-14}$ m <sup>2</sup>
Compensation chamber	Material	316L SS
	O.D.	4.394 cm
	Length	8.025 cm
	Volume	115 cm <sup>3</sup>
Transport lines	Material	304L SS
	I.D.	0.452 cm
	Wall thickness	0.508 mm
	Vapor line length	1.00 m
	Liquid line length	1.074 m
Condenser	Material	6063 AL extrusion
	I.D.	0.399 cm
	Wall thickness	7.62 mm
	Length	3.81 m
Propylene	Charge	80 grams
	Purity	99.9%
Heating block	Material	6061 AL
	Dimension	7.62 cm by 15.24 cm by 1.91 cm
	Mass	0.5 kg
Cooling block	Material	6061 AL
	Dimensions	7.62 cm by 15.24 cm by 1.27 cm
	Mass	0.5 kg
Large mass (each block)	Material	Copper
	Dimensions	7.62 cm by 20.32 cm by 2.54 cm
	Mass	3.5 kg

Under these conditions a maximum of 7% of the heater power applied to the large mass is delivered to the LHP evaporator saddle to develop the superheat required to initiate boiling. This represents the maximum power available to the evaporator for startup because parasitic heat leaks will only reduce the available power.

In flight applications, this is a system-level issue that requires evaluation to assess potential risks. This problem can potentially be compounded for systems that power-up at a reduced power dissipation state. In this situation, it may be desirable to add heaters, which serve both as startup and supplemental heaters, to the evaporator. To mitigate this problem, its important to minimize the effective thermal mass of the equipment attached to the evaporator. This is accomplished by providing thermal isolation to the mounting interface and the surrounds.

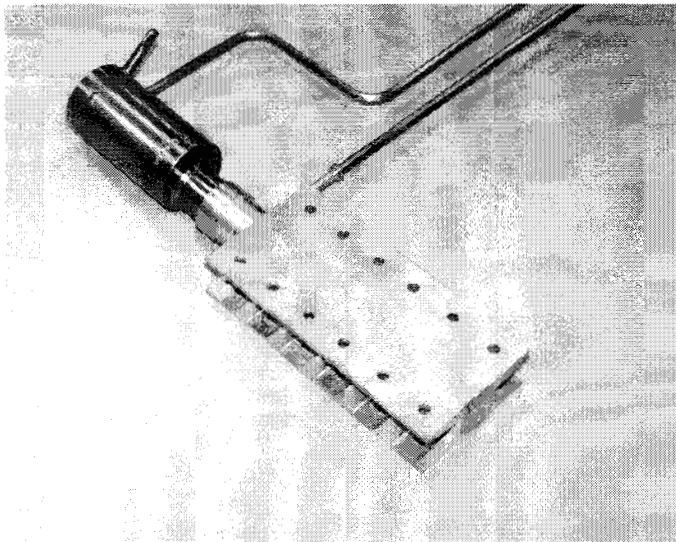


Figure 5. LHP evaporator and compensation chamber: close-up view

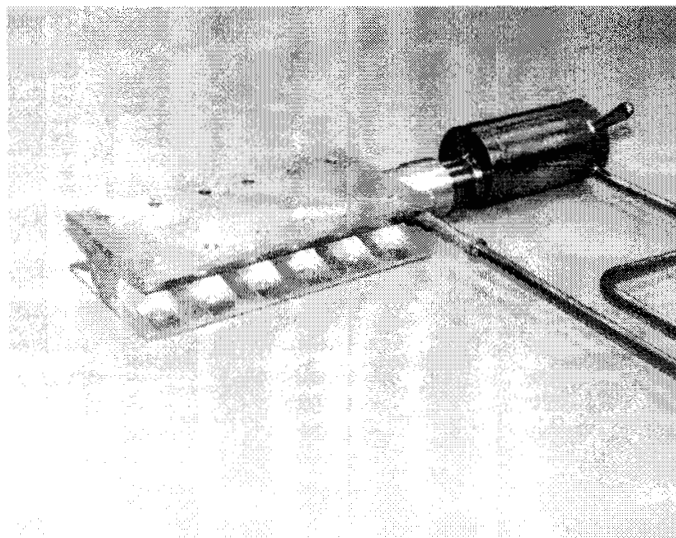


Figure 6. LHP evaporator and compensation chamber

Two startup heaters placed in different locations were implemented to study the startup behavior. A Minco Kapton thin film heater was bonded to the transition tube

on the aluminum side and on the evaporator saddle between the two mounting flanges. Fig. 11 shows the location of both startup heaters. Placing the heater on the transition tube rather than the evaporator saddle creates a larger localized heating effect near the vapor exit line. Two thermocouples were placed on the transition tube near the heater to monitor the localized temperature rise. The same heater was used in both locations. The heater was sized for 10 W maximum and its size was 0.55 inch by 1.2 inch. The startup heater was powered with 5-12 W, which results in a heat flux of 7.6-18.2 W/in<sup>2</sup>.

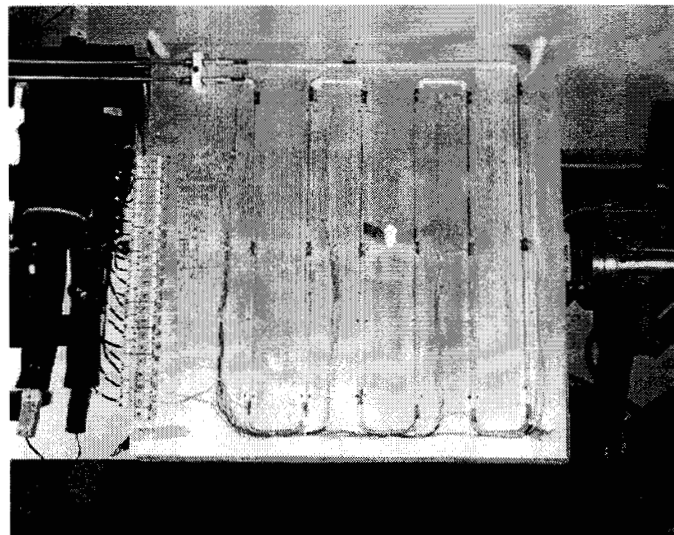


Figure 7. LHP Condenser attached to aluminum plate

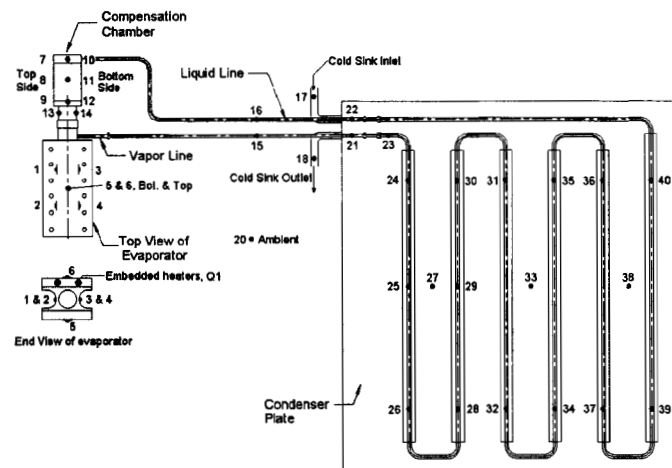


Figure 8. Schematic of LHP with test thermocouples

## TEST PROGRAM

Thermal testing was carried out at various initial temperature conditions for the condenser and evaporator as well as power levels. Evaporator power and initial

temperature was varied from 10 to 100W and  $-30$  to  $20^{\circ}\text{C}$ , respectively. The startup and shutdown tests are a subset of the complete characterization tests performed on this unit.

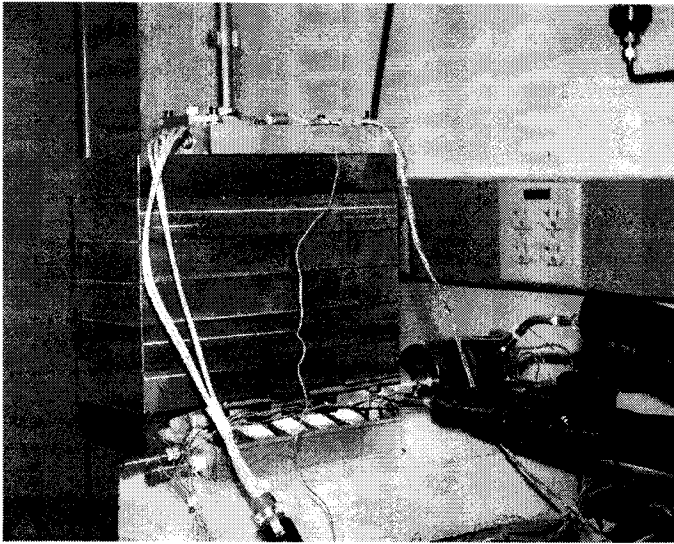


Figure 9. LHP evaporator with large mass: view of cooling block heat exchanger on bottom

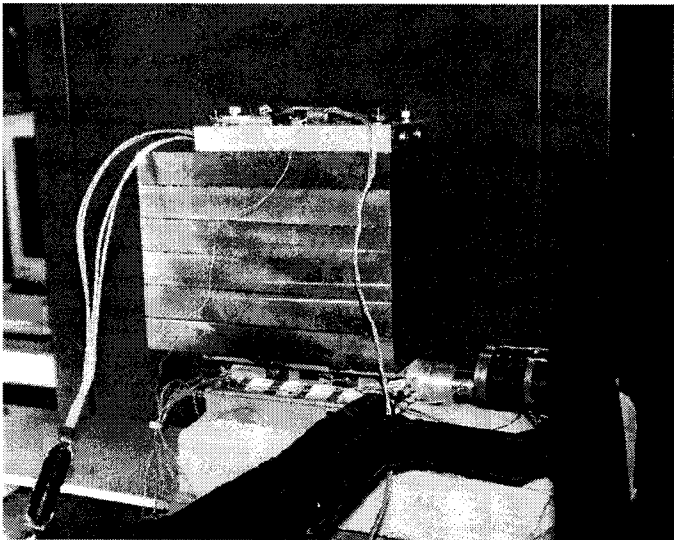


Figure 10. LHP evaporator with large mass: view of heating block on top

This paper reports only on test results for startup and shutdown. Startup tests were only performed for the horizontal position where condenser and evaporator are approximately at the same elevation and with the large mass attached to the evaporator. This was done to simulate on-orbit microgravity conditions for the TES LHPs.

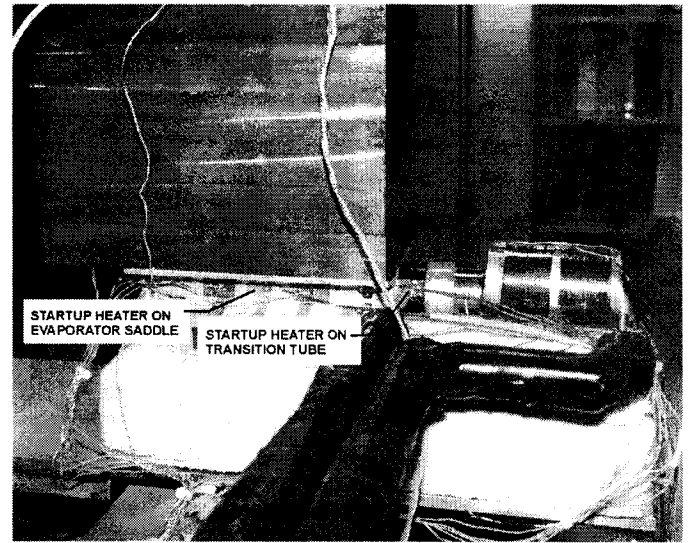


Figure 11. Startup heaters on evaporator

## SUMMARY OF TEST RESULTS

Typical transient results with no startup heater are shown in Figs. 12-15. The evaporator and compensation chamber temperatures plotted are average from four and six thermocouples, respectively. Table 2 correlates the temperature labels used in the plots with the thermocouple location from Fig. 8. Qevap is the power applied to the heater block at the evaporator and Qheat is the startup heater power. The evaporator power varies from 25 W to 100 W and the sink temperature from  $-30$  to  $10^{\circ}\text{C}$ . These test results show that the LHP preferentially starts at an evaporator temperature between  $35$  and  $40^{\circ}\text{C}$ . The superheat measured as the evaporator minus the compensation chamber temperature varies from  $1$  to  $2^{\circ}\text{C}$ . In all these cases, 10 W was applied to the compensation chamber for 10 minutes at the end of each test to flood the vapor grooves providing consistent initial conditions for the following test. Figs. 16-20 show results with a startup heater on the evaporator saddle flange as shown in Fig. 11. Low evaporator power was used varying from 15 to 30 W and with 10 W applied to the startup heater. The additional heat from the startup heater increased the superheat until startup. In this case, the LHP started when the evaporator reached higher temperatures between  $40$  to  $45^{\circ}\text{C}$ . Startup occurred with a superheat between  $1.5$  to  $2^{\circ}\text{C}$ . Transient results with a startup heater located on the transition tube between the evaporator and compensation chamber are shown in Figs. 21-24. Power to the evaporator was varied from 15 to 25 W and the sink was varied from  $-30$  to  $20^{\circ}\text{C}$ . The startup heater power was 10 W. The results from Figs. 21 and 22 show the LHP starts immediately after power is applied. Once the LHP starts, additional heat from the startup heater conducts to the compensation chamber raising the saturation temperature, and thus, increasing



the temperature of the evaporator as shown in the figures. The results from Figs. 23 and 24 show results, which indicate a fail startup when power is applied to the startup heater. However, when the startup heater is turned off, the LHP starts immediately. These results indicate that the fluid motion created by heating the liquid and/or vapor in the transition tube creates favorable conditions to initiate boiling on the wick surface. When the heater is turned off, fluid motion is again created having a similar effect. However, LHP startup is not guaranteed when power is applied or removed to the startup heater.

Test results have demonstrated excessive temperature overshoots under demanding initial conditions. Prior conditions play an important role in startup, but do not seem to effect steady state thermal performance. When the vapor grooves are liquid filled, the superheat required to initiate boiling is greater, and therefore, the overshoot tends to be greater under these conditions. Consistently, the worst case overshoots were observed when heat was applied to the compensation chamber for a few minutes and then the LHP remained undisturbed for a few days prior to initiating startup. At power levels greater than 25 W, the LHP starts at temperatures between 35 and 40°C independent of sink temperatures. At lower power levels, the start temperature increases to 40-45°C. Once the LHP starts and the startup heater is turned off, it always remains functioning as long as power is applied to the evaporator.

The superheat required to start varies from 1 to 2°C for conditions with a startup heater between the evaporator flange and without a heater. Generally, with warm conditions the LHP was able to start within 2-5 minutes. Results for the startup heater on the transition tube show favorable starts in some cases. However, more testing is needed to fully understand the phenomena observed.

Results also show that for all conditions, when power was removed from the large mass/ evaporator, the LHP always immediately stops functioning.

Table 2. Definition of temperature labels

Plot Label	Thermocouple No.
Tevap	TC1 – TC4 Average
Tcc	TC7 – TC12 Average
Tliq-exit	TC22
Tliq	TC40
Tvap-in	TC21
Trad	TC27, TC33, TC38 Average
Tvap	TC24
Tamb	TC20

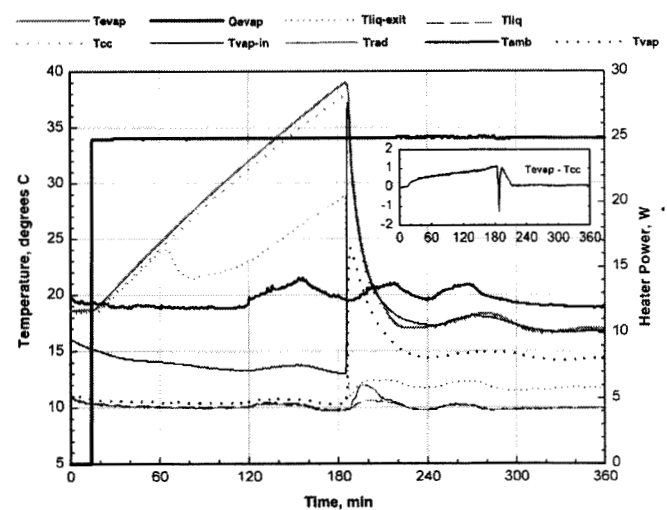


Figure 12. Results for 25W to evaporator and no startup heater

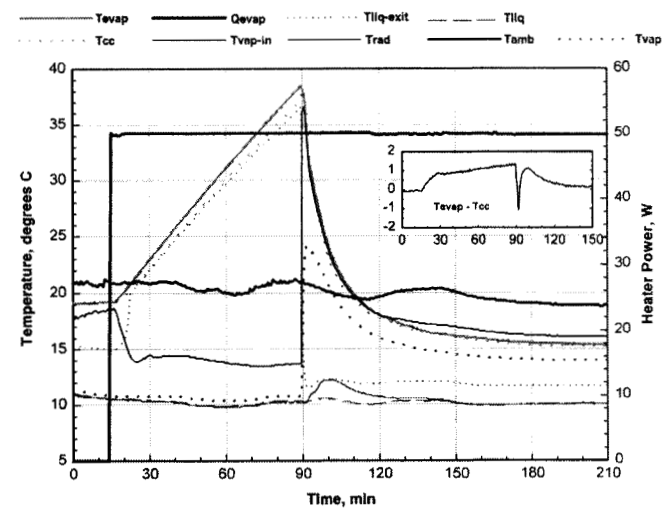


Figure 13. Results for 50 W to evaporator and no startup heater

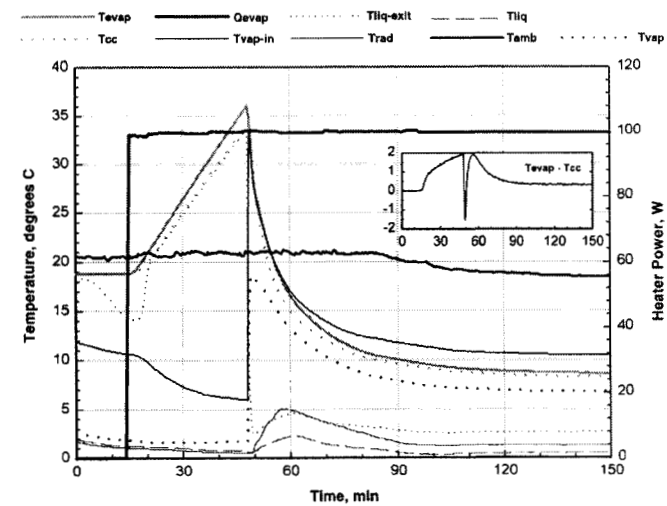


Figure 14. Results for 100 W to evaporator and no startup heater

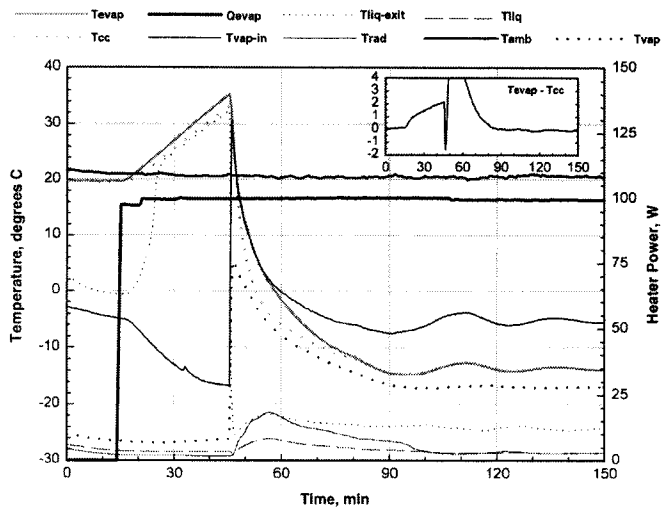


Figure 15. Results for 100 W to evaporator and no startup heater

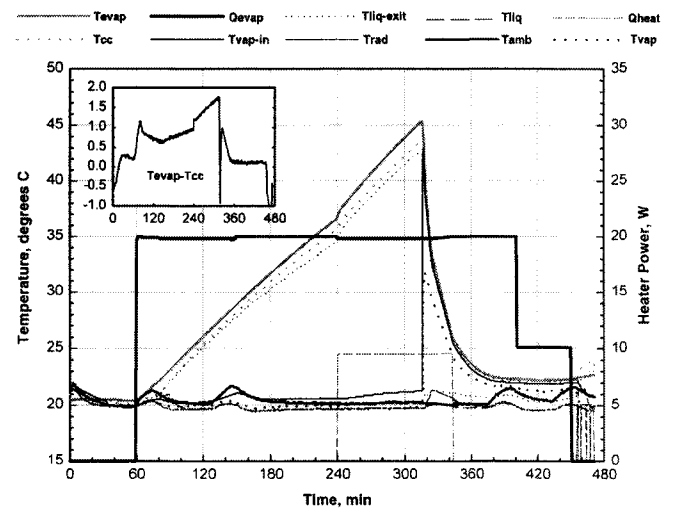


Figure 18. Results for 20 W to evaporator and 10 W startup heater at evaporator flange

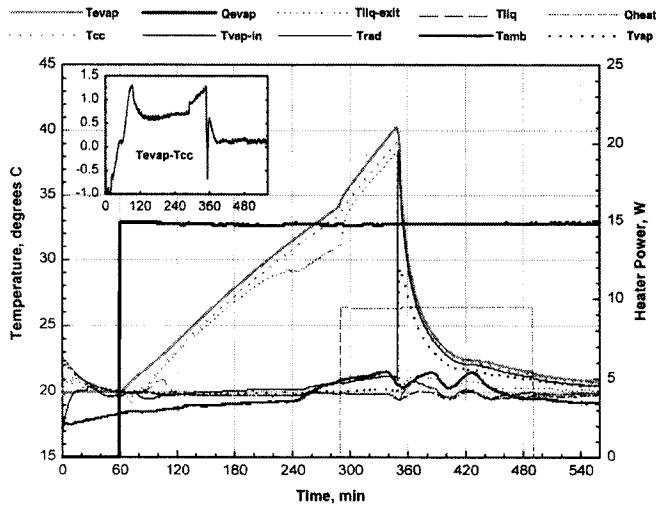


Figure 16. Results for 15W to evaporator and 10 W startup heater at evaporator flange

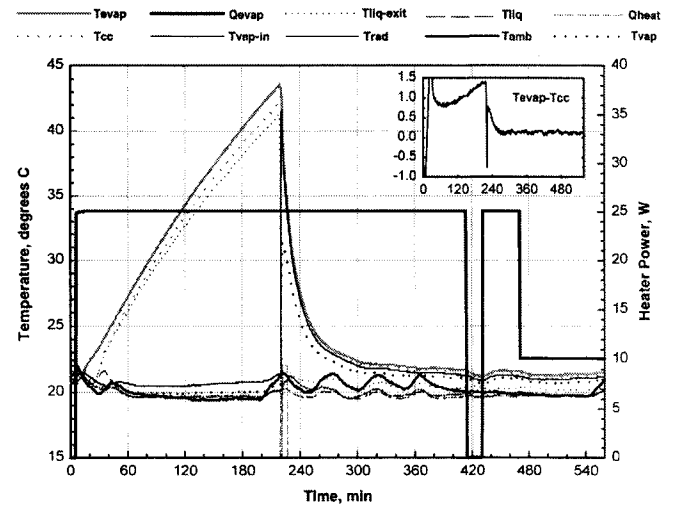


Figure 19. Results for 25 W to evaporator and 10 W startup heater at evaporator flange

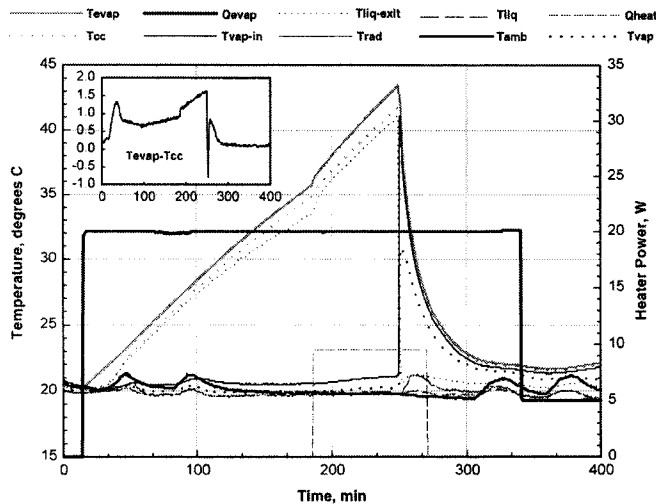


Figure 17. Results for 20 W to evaporator and 10 W startup heater at evaporator flange

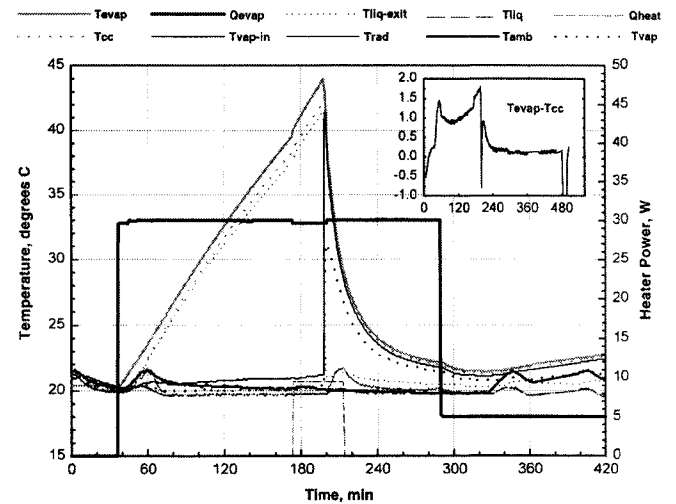


Figure 20. Results for 30 W to evaporator and 10 W startup heater at evaporator flange

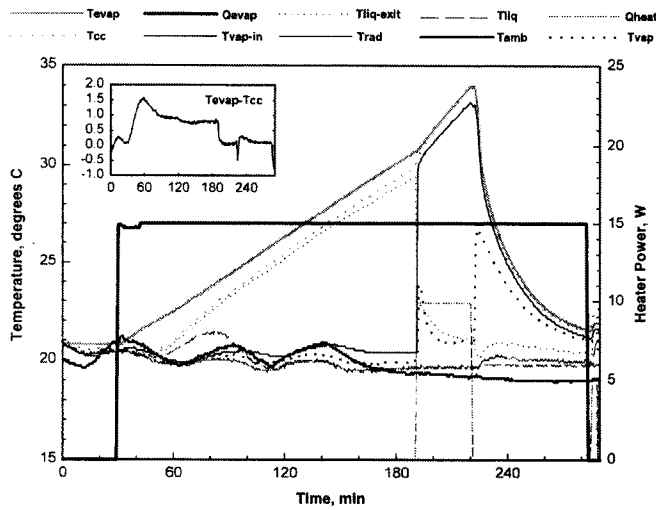


Figure 21. Results for 15 W to evaporator and 10 W startup heater at transition tube

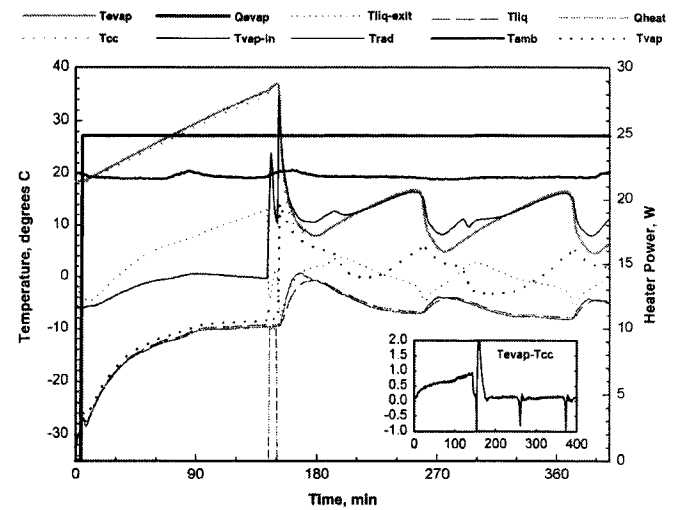


Figure 24. Results for 25 W to evaporator and 10 W startup heater at transition tube

## CONCLUSION

Extensive testing has been performed on a propylene LHP technology demonstration unit of similar design to the flight units for the TES instrument. Evaluation of test results indicates a need for a startup heater during on-orbit operations for TES. Test conditions were focused towards the specific flight requirements for TES. The TES flight LHPs will incorporate a startup heater with redundancy.

The startup phenomena observed indicate that for conditions when the vapor grooves are liquid filled, excessive temperature overshoots can result. Under some initial conditions temperature overshoots exceeding 25°C were observed. In general, lower power and sink temperatures produced higher overshoots. The startup heater, placed on the transition tube, was most effective with warm evaporator startup conditions and at cold temperatures, less than 20°C, failed to start the LHP. At low power levels and cold conditions, the parasitic heat leaks become increasingly more important and severely impact conditions for a successful startup.

When comparing propylene and ammonia, in terms of the superheat required to initiate nucleate boiling, ammonia requires 10 times more superheat near room temperature. This factor increases to 20 times at -30°C. The thermal conductivity of propylene is about 22% that of ammonia, which reduces the effective wick conductivity resulting in a lower parasitic heat leak into the liquid core. In theory, propylene LHPs should have fewer problems starting when compared to ammonia LHPs. However, this appears not to be the case after careful evaluation of the test results from JPL's technology evaluation LHP. It is interesting to note that the latent heat of vaporization of propylene is only about 30% that of ammonia. If vapor is present in the vapor

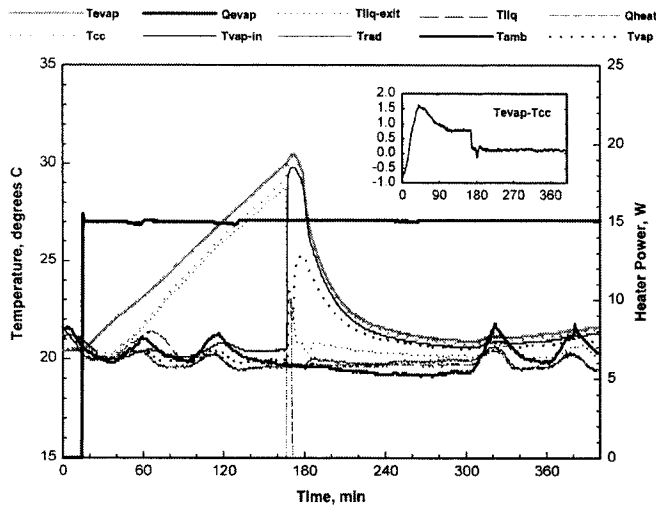


Figure 22. Results for 15 W to evaporator and 10 W startup heater at transition tube

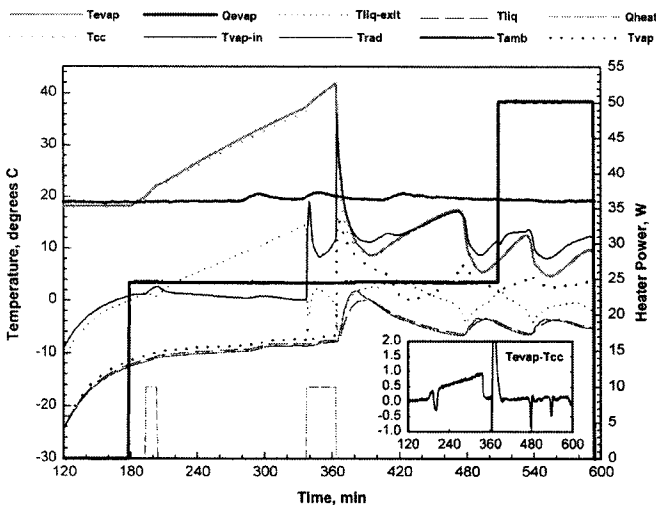


Figure 23. Results for 25 W to evaporator and 10 W startup heater at transition tube



grooves, the energy required for the inception of boiling is small and startup occurs without much difficulty. However, if the vapor grooves are liquid filled and there is vapor present in the liquid core, the parasitic heat leak through the wick maybe enough to initiate boiling inside. This is a detrimental effect, making it more difficult for startup. Additional testing is required to fully understand the dynamics of startup. It is recommended that transient testing be done with other fluids to determine the influence of thermophysical properties.

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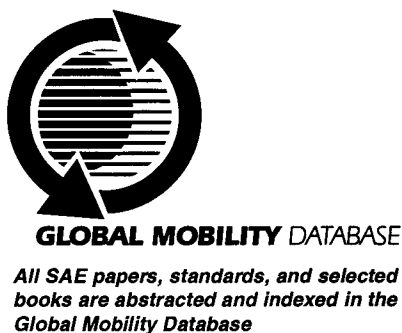
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